Microrelays With Bidirectional Electrothermal Electromagnetic Actuators and Liquid Metal Wetted Contacts

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***Abstract*—Microrelays with liquid metal wetted contacts have been demonstrated using bidirectional electrothermal electromagnetic actuators. These relays were fabricated with the MetalMUMPs foundry process, which has a 20-μm-thick nickel structural layer. The operating voltage is under 0.5 V. The measured breakdown voltage and OFF-state resistance are greater than 200 V and 100 MΩ, respectively, and the gold-to-gold contact resistance is around 0.3 Ω. When the contacts are wetted with liquid gallium alloy (melting point at -20 °C), the measured contact resistance can be as low as 0.015 Ω. As such, these bidirectional relays could have potential applications in high-power switching systems with low contact resistance using liquid metal wetted contacts. [1706]**

***Index Terms*—Bidirectional actuators, electromagnetic, electrothermal, liquid metal, MetalMUMPs, microrelays.**

I. Introduction

SINCE the early 1970s [1], various types of microrelays have been demonstrated based on micromachining technologies for applications in telecommunications, automotive, and other systems. In general, mechanical relays with metal-to-metal contacts are preferred over solid-state relays because they have high breakdown voltage, low ON-state resistance, and good linearity. Various actuation mechanisms have been used in microrelays, including electrostatic, electrothermal, and electromagnetic actuation. Among these, electrostatic actuation [2]–[19] is the most popular approach because it provides fast response time and consumes little power. However, electrostatic actuation force is typically weak, resulting in high contact resistance and possible contact welding during relay operation. In order to enhance the actuation force, microrelays based on electrostatic driving mechanism commonly use high driving voltages and have small separation gap between electrodes, large electrode areas, and compliant suspension structures.

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Microrelays driven by electrothermal force, on the other hand, can exert higher force and achieve lower contact resistance and reliable separation. However, the response time tends to be slow, and power consumption is high [20]–[27]. The driving voltage is typically low for electrothermal microrelays, but the applied current tends to be high. The voltage and current requirement is largely dependent on the resistivity and geometry of the actuator. The third category of mechanical microrelays uses electromagnetic actuators to provide high force and large displacement. Unfortunately, the fabrication process tends to be very complicated [28]–[37], as thick conducting layer(s) may be required to fabricate the electromagnetic coils. High-permeability materials may also be necessary to fabricate the magnetic cores. In addition to the fabrication complexity, electromagnetic microrelays also consume significant amount of power, as large electrical current is required for operation.

Further literature review shows that researchers have used the PolyMUMPs foundry process with various postprocessing steps to construct dielectric layers in fabricating microrelays [21], [22], [26], [37]–[40]. The dielectric layer can mechanically connect the electrodes but electrically isolate the contacts for microrelay applications. These postfoundry processing steps include the use of benzocyclobutene photo-patternable polymer or photoresist as the dielectric interconnect. In either case, reliability of the polymer material and large lateral contact resistance are two key issues to be further investigated and addressed. This paper uses the MetalMUMPs process to build microrelays with two distinctive achievements, including the use of the electrothermal electromagnetic bidirectional actuator [42] as the actuation source and liquid metal wetted contacts to improve the contact characteristics [43].

II. Relay Design and Operation Principle

Fig. 1 shows the schematic diagram of the microrelay based on the MetalMUMPs process. The bidirectional actuator [42] is based on straight electrically conductive fixed-fixed beam design and it controls the movement of the moving contact to open or close the relay. In this paper, microrelays use up to twelve actuation beams with lengths between 1700–2400 μm, width of 10 μm, and thickness of 20 μm. These actuators can achieve displacement over 50 μm and exert force greater than 3 mN in both directions. The MetalMUMPs process allows the actuators to be built on top of a 25-μm-deep thermal isolation trench, as illustrated in Fig. 1. Trenched actuators have better energy efficiency than the nontrenched

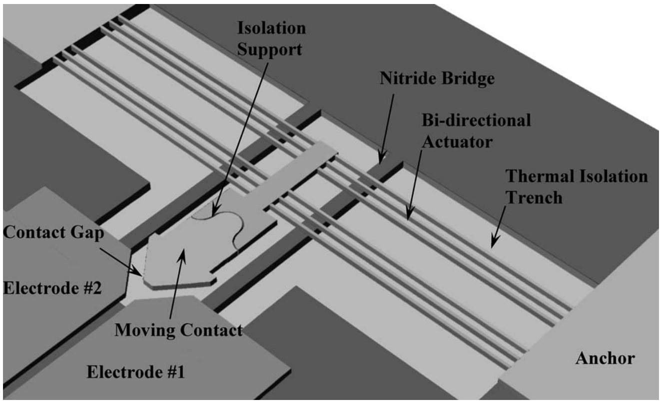


Fig. 1. Schematic diagram of the microrelay.

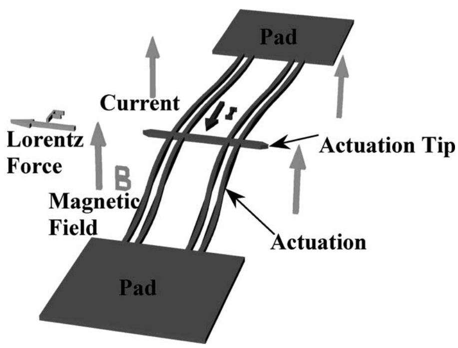


Fig. 2. Working principle of the bidirectional electrothermal electromagnetic actuator. When the electrical current (I) is applied from one pad through the actuator beams to the second pad, Lorentz force (F) is generated when the current interacts with the external magnetic field (B). The beam will buckle due to thermal expansion, and the in-plane buckling direction is controlled by the direction of the Lorentz force.

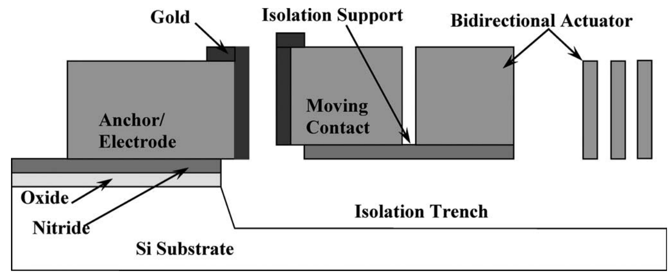
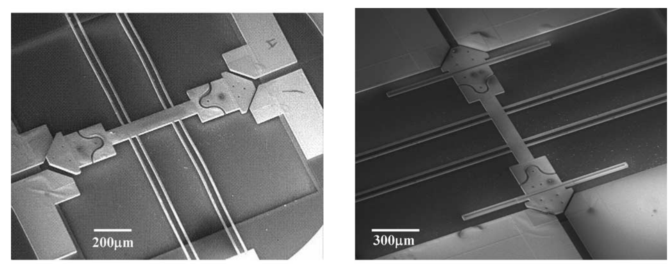


Fig. 3. Cross-sectional view of the bidirectional microrelay based on the MetalMUMPs process showing the gold overcoat layer to improve the contact characteristics.



(a) (b)

Fig. 4. SEM microphotos showing two fabricated microrelays. Both relays have no nitride bridge and can perform SPDT function. (a) Four-beam bidirectional actuator is utilized. (b) "Spring-loaded contact" design is applied.

actuators [41]. The isolation support made of silicon nitride is critical in microrelay designs as it provides electrical/thermal isolation but mechanical connection. The two nitride bridges help protect the device from excessive vertical movement during operation. Fig. 2 illustrates the working principle of the bidirectional electrothermal electromagnetic actuator. When electrical current (I) passes from one pad through the actuator beams to the second pad, thermal expansion of the beams can cause buckling and generate actuation force. The electro-thermal-structural behavior of these beams can follow previous analysis and simulations based on a micromachined fixed-fixed beam structure [41]. Analytically, for a 2000-μm-long 10-μm-wide 20-μm-deep beam made of nickel, the smallest critical load to cause buckling is 3.6 mN or 18.2 MPa in stress, and the corresponding average temperature rise of the beam is 7 °C. Maximum displacement of 50 μm in some relays can be achieved with an average temperature rise of 240 °C. Smaller displacements such as 20 μm can be achieved with an average temperature rise of 40 °C. A permanent magnet is placed below the actuators to have its magnetic field lines perpendicular to the moving plane of the actuator. Lorentz force (F) generated by the current interacting with the external magnetic field (B) controls the buckling direction.

Microrelays are tested by placing them on top of a 1-in-diameter 0.25-in-thick permanent magnet with a 0.3-T flux density. A big magnet is used for easy handling although a much smaller magnet can be used without affecting the microrelay performance. It is important to place the relay close to the center of the magnet, or the actuator might twist out of plane causing misalignment between the moving and fixed contacts. The nitride bridge design confines this twisting motion and helped in alleviating the problem.

The microrelay contact must satisfy several requirements in this paper. First, the moving contact has to make a firm connection with both stationary electrodes. Second, it has to survive the process variations that might alter the shape of the contacts and prevent intimate contact. Third, it must have a large contact area to allow the passage of large current. The 45-° wedge design was chosen because of its ability to self-alignment when the relay is closed. The typical width of the wedge used in the prototype device is 250 μm, and the dimension of the air gap between the contacts varies between 20 to 50 μm. Previously reported breakdown voltage for a 5-μm metal-air-metal gap is 360 V [44], [45]; hence, the gap size used in our design is more than adequate for the voltages being switched.

Fig. 3 shows the cross-sectional view of the bidirectional relay. It is noted that both the fixed and the moving contacts are coated with a layer of 2-μm-thick gold to improve contact characteristics. The nitride isolation support consists of a 0.7-μm-thick nitride connecting two 20-μm-thick nickel structures, and the typical gap in the isolation support is 8 μm. Fig. 4(a) shows the SEM microphoto of a fabricated single-pole double-throw (SPDT) microrelay. In this device, a four-beam bidirectional actuator is used without any nitride bridges. Fig. 4(b) is a microrelay built with spring-loaded contacts. The spring flexure serves several purposes. First, the spring flexure acts as the force buffer to compensate for process variations from sample to sample. Second, the spring flexure serves as heat isolation buffer between the contact and the actuator. For example, if a current of 4-A passes through a contact with resistance of 0.3 Ω, the heat generated at the contact is 4.8 W. This may cause additional thermal expansion and affect the performance of the actuator. Third, the spring flexure provides quantitative data on the force applied to close the contact. A general rule of thumb, a clean gold-to-gold contact needs at least 100 μN of force to achieve a contact resistance of 0.1 Ω [46]. The spring flexure used in this prototype relay has a spring constant of 100 $\mu\mathrm{N}/\mu\mathrm{m}$, and the gap between the mechanical flexure is 6 μm. Therefore, before the flexure is fully compressed, the total force keeping the contacts together is from 0 to 600 μN pending on the deflection of the spring. The drawback of the spring relay is that it reduces the actuation and separation force that can be applied onto the contacts. Analytically, the apparent contact area of the relays is 0.0056 mm^2. Assuming an actuation force of 1.5 mN, the contact pressure is 190 kPa, and the calculated contact resistance per unit surface is about 53 Ω/mm^2.

III. Fabrication

A. MetalMUMPs Process

The microrelays are fabricated using the MetalMUMPs [47] process, with additional postprocessing steps. The MetalMUMPs process uses 8 thin films, 6 masks, and the main structure is constructed of a 20-μm-thick electroplated nickel layer. The nickel film fabricated using this process can vary from run to run, and the one we have used exhibits tensile residual strain in the order of 900 $\mu\varepsilon$. The metallic structures can be mechanically connected and electrically isolated using the silicon nitride isolation support, as illustrated in Fig. 1. The process used to form the nitride isolation support is quite complicated, using three structural layers, two lithography steps, and two etching steps. In order to reduce the contact resistance, MetalMUMPs process include an electroplating step to deposit an overcoat of 2-μm-thick gold layer on the top and sidewall of contact structures. However, this gold overcoat layer can be very rough as shown in the SEM microphoto in Fig. 5. The estimated rms roughness of the gold overcoat is 1 μm, as observed in the figure such that the true contact area is only a small fraction of the apparent area brought into contact. Furthermore, the two contacting surfaces are often covered with oxide or other electrically insulating layers; the interface becomes electrically conductive only when metal-to-metal contact spots are produced. This occurs when the insulating films are ruptured at the contact surfaces. The true contact area at this scale is determined primarily by the applied force, hardness of the contact material, and the resistance to forming surface layers. Previous literature claims that a clean gold-to-gold contact with 0.7-Ω contact resistance has an actual contact area of 0.125-μm in radius [47].

B. Liquid Metal Wetted Contact

In order to improve the contact characteristics, a thin layer of liquid metal could be coated on the contacts and fill the surface roughness to improve the contact characteristics, as illustrated in Fig. 6. The low modulus of a liquid versus a solid can significantly reduce the need for a large contact force. This idea has been used for decades in macroscale mercury switches. Mercury relay was invented by Bell Labs in 1940 [48], and many mercury relays are commercially available [49]–[52]. Mercury is very conductive (96 $\mu\Omega\cdot$cm) and has a low melting temperature of −38 °C. Macroscale mercury displacement relays can switch hundreds of amperes with contact resistance less than 50 MΩ. Electrical connections are opened and closed by immersing and lifting electrical contacts from a pool of mercury. The mercury pool also acts to quickly quench the heat generated during arcing. Furthermore, since there is no solid metal-to-metal contact, contact welding is not a problem. However, mercury is highly toxic, and our goal is to find an alternative metal or alloy that have low melting temperature, high boiling point, high electrical conductivity, and can wet contact materials commonly used in microelectromechanical systems relays, such as gold. Galinstan fluid, a nontoxic alloy, was chosen in this paper as it has a low melting temperature of −20 °C and a boiling temperature greater than 1300 °C. The main ingredients of this Galinstan fluid are gallium and indium, both have the capability to wet many metals, including gold. The resistivity of Galinstan fluid is 43.5 $\mu\Omega\cdot$cm [53].

Experimentally, Galinstan fluid was evaporated on to the MetalMUMPs chip using a thermal evaporator. The evaporation rate and film thickness are measured using a crystal monitor,

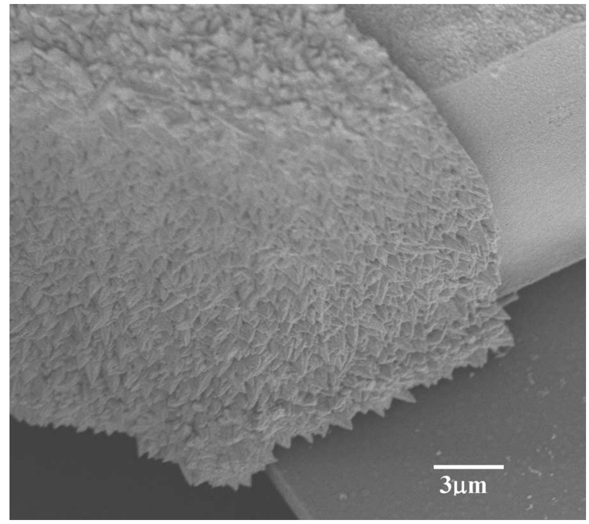


Fig. 5. SEM microphoto showing the 2-μm-thick gold overcoat layer. The rms roughness of overcoat gold layer is about 1 μm, which is much larger than the grain size on the structural layer.

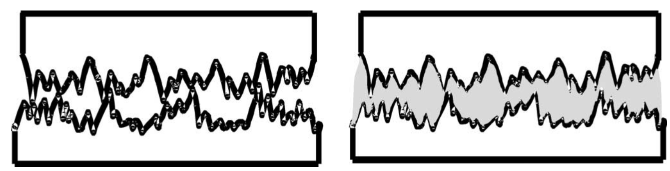
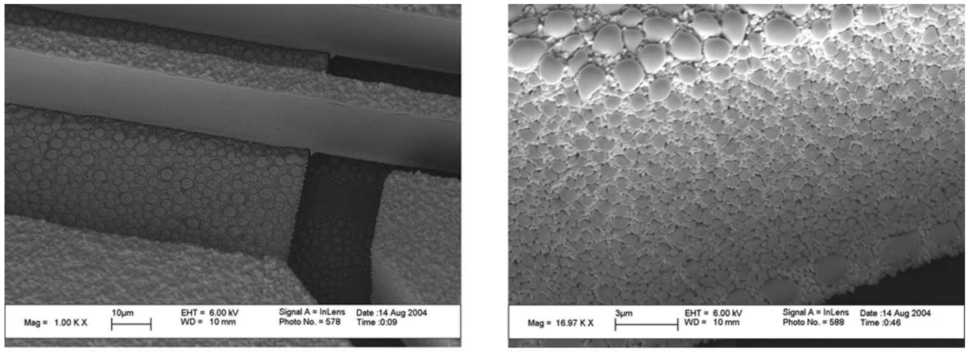


Fig. 6. Left: Actual contact areas between two surfaces are very small, only a few points are in contact. Right: Real contact area increases when the gap is filled with liquid metal.



(a) (b)

Fig. 7. 0.1-ml liquid metal deposition test. (a) Isolated beads of liquid metal forms on top of the structure. (b) Beads about 1 μm in diameter on the top surface of the gold contact and less than 0.5 μm in diameter on the sidewall.

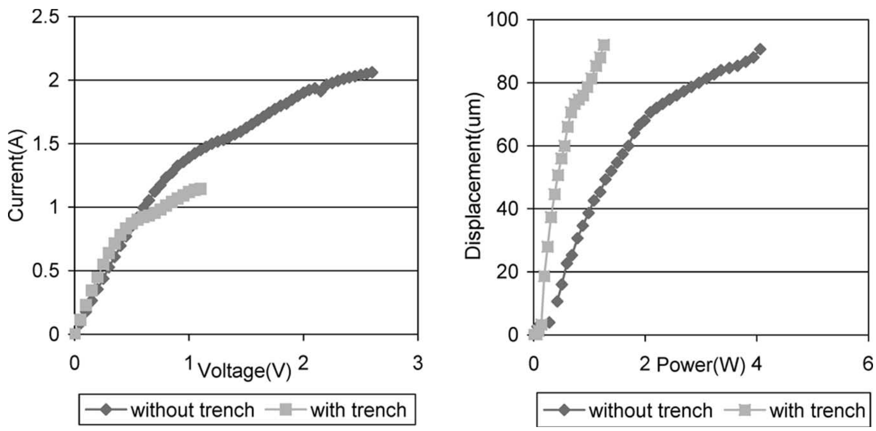


Fig. 8. Left: Measured I–V responses of actuators with and without trench. Right: Power versus displacement curves of the bidirectional actuators.

but the liquid metal causes the monitor to quickly fail. Before the failure, a correlation between the evaporation rate and chamber pressure can be established. The evaporator used for the liquid metal evaporation is designated for various material depositions, and no problem has been reported after the liquid metal process. It is found that the evaporation rate should be kept below 10 Å/s to ensure good film thickness control. If the liquid metal film is too thin, no decrease in contact resistance can be observed. If the liquid metal film is too thick, the relay is shorted as a continuous film of liquid metal that covers the entire device. The film thickness in this paper is controlled by dispensing a measured amount of Galinstan fluid into tungsten evaporation boats. MetalMUMP chips are first taped to a silicon wafer using double sticky tape to have the chips facing the evaporation sources. It is desirable to have liquid metal coated on the sidewall where the actual contact takes place. However, this is relatively difficult due to the strong shadowing effect in the evaporation process. Experimentally, we place the die at an angle from the evaporation source and rotate the chips several times during the evaporation process.

When 1.0 ml of Galinstan fluid is evaporated onto the relays, the entire relay is covered by liquid metals, causing both mechanical and electrical failure. Evaporating 0.6 ml of liquid metal still causes most relays to fail. When 0.35 ml of Galinstan fluid is evaporated on the relay, a continuous film of liquid metal is formed on the areas covered with gold, while individual beads of liquid metal form on the areas covered with silicon nitride. This provides satisfactory electrical isolation, but none of the fabricated relays can function properly as they are easily shorted after one operation. The results on 0.1 ml of liquid metal deposition, as shown in Fig. 7, lead to the formation of small liquid metal beads on the contact surfaces. Most liquid metal still end up at the top surface, but there is enough deposition on the side surfaces to produce measurable reduction in resistance. Although selective deposition of liquid metal is preferred, it was impossible to conduct patterning and thin film deposition on the released MetalMUMP chips. A possible alternative is to use a shadow mask with a good alignment tool for selective deposition; this will be further investigated.

IV. Experimental Results and Discussions

A. Bidirectional Actuators

The actuation force of the bidirectional actuators with and without thermal isolation trench is characterized in a normal laboratory environment without packaging. The trench design can help insulate heat conduction from the actuator to the substrate. I–V curves and the displacements versus power curves of both types of actuators are shown in Fig. 8. These were

TABLE I
RELAY ACTUATOR DIMENSIONS, MEASURED OPERATING VOLTAGE, AND CURRENT

Beam Length (μm)	# of Beams	Contact Gap (μm)	V Closing (Volt)	I Closing (Ampere)
1700	4	20	0.2	0.4
2400	6	50	0.25	0.75
2400	12	50	0.5	0.8

testing the results for six-beam bidirectional actuators with length of 2000 μm and width of 10 μm. The testing results show that actuators built on top of a 25-μm-deep thermal isolation trench are about three times more energy efficient in achieving the same actuation displacement. It is noted that under high driving voltage, the driving current becomes lower for the device with trench than the one without trench. Analytically, devices with trench have better heat insulation such that they have higher temperature under the same input voltage. Due to positive temperature coefficient of resistivity, devices with trench will have higher resistance and lower driving current under the same voltage at high temperature. The variations under low driving voltage come from the variations in the probe contact resistance since the driving voltage is very low, but the current is high, and a small amount of added contact resistance can skew the results. These actuators can achieve lateral deflection over 50 μm with less than 2 V for the nontrenched actuators and less than 0.5 V for the trenched actuators. The current requirement, on the other hand, is relatively high. The large amount of heat energy required to operate these actuators makes their response time limited to the heat transfer process. The maximum operating speed ranges from several hertz to several tens of hertz, depending on the number of actuation beams. Actuators with more beams require more time to cool down such that their response time is slower. As a result, relay reliability tests are run at 1 Hz, and other tests are run manually. Actuation force is experimentally measured by having the actuator push against cantilever beams with known dimensions [42]. Table I lists typical operation voltage and current of the relay actuators used in these prototype devices. Under first-order approximation, if the number of beams would double, the driving current would double to reach a similar temperature state for mechanical actuation. In practice, it is observed that when the number of beams has doubled, each beam heats up its neighbor more easily such that smaller current level can reach the right temperature state for thermal actuation, as observed in Table I. Furthermore, since the resistance of the structure is very small, a small amount of added contact resistance from the probe tip can skew the results. In the relay applications, the typical operation voltage and current of the actuators are between 0.2–0.5 V and 0.4–0.8 A.

These bidirectional actuators are very reliable; some actuators have been tested for over one million cycles without failure [42]. Bidirectional relays with spring loaded contacts have been cycled for more than 100 000 repetitions (flexures fully compressed such that more than 600 μN of contact force was exerted during each cycle) without failure, and there was no sign of wear or deformation at the contact surfaces. The main failure mechanism for spring-loaded relays is contacts moving out of the plane vertically from each other. Although this type

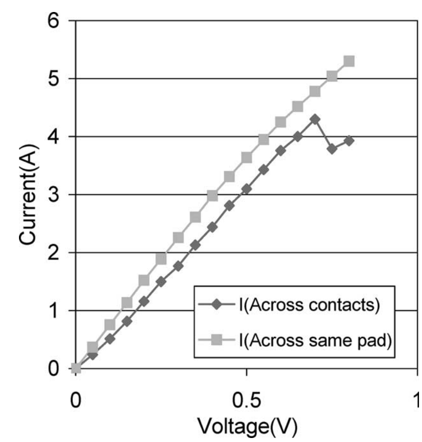


Fig. 9. Measurements of I–V curve hot switched by the relay across the contacts and I–V plot of two probes on the same pad. These results are used to measure parasitic resistance of the measurement setup.

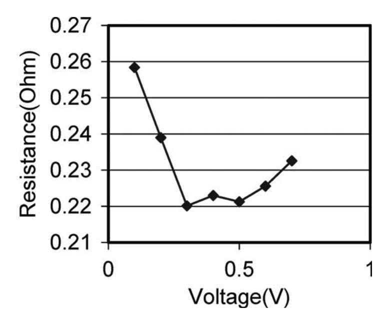


Fig. 10. Contact resistance measurement of a gold-to-gold contact under various carrying voltage across the contact.

of failure occurs in nonspring-loaded contacts too, the extra flexibility provided by the springs makes out of plane slipping easier.

B. Contact Resistance

The contact resistance in a metal-to-metal contact is properly known as constriction resistance. Current passing through the constriction point causes a rise in temperature and decreases the yield stress in the contact material. If the contact force remains constant, the actual areas of contact will increase. This causes a negative thermal feedback as the thermal softening increases the true contact areas and decreases thermal power dissipated. Awareness of this phenomenon is very important since relay contact resistance specified at datasheets can be very misleading. A relay might specify a 0.1-Ω contact resistance while passing 1 A. When the contacts of this relay are first closed and low voltage and current is passed, the contact resistance could be much higher than specified. When higher

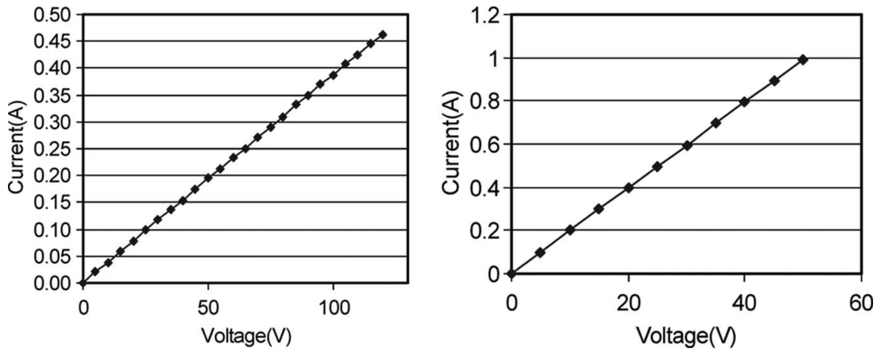


Fig. 11. Voltage and current hot switched over a 250-Ω resistor (left) and a 50-Ω resistor (right) using microrelay with gold-to-gold contacts.

voltage and current is applied, the contact resistance could drop to less than 0.1 Ω as specified.

Contact resistance of our relays is measured using a multimeter via two probe tips to measure the resistance from one fixed electrode, to the moving contact, and to the other fixed electrode. The probe tips are then moved to the same pad to measure the parasitic resistance that forms the probe tips and wires in the testing setup. Fig. 9 shows one typical contact resistance measurement result. The difference between the two measurements is considered as the actual contact resistance, which include the bulk resistance of the moving contact and electrodes, and the two interface between the moving contact and fixed contacts. The measured contact resistance of these relays with gold-to-gold contact as fabricated is typically 0.3–0.4 Ω under a nominal bidirectional actuator operation power of 0.3 W with an estimated force of 1 μN. The bulk resistivity of 20-μm nickel and 0.5-μm gold composite structure is approximately 0.003 $\Omega/\square$; hence, the two surface contacts are the major contributors to the contact resistance. Relays with clean gold-to-gold contacts have many characteristics of an ideal switch. The measured OFF-state resistance is over 100 MΩ, and the breakdown voltage exceeds 200 V; these are the limitations of the multimeter and power supply used for the tests.

Fig. 10 shows one contact resistance measurement result under increased carrying voltage. As high current is passed through the contacts, the contact resistance decreases as more contact areas are established due to local heating and softening. When the input power is further increased, the contact resistance increases due to the contact heating. In our experiments, most gold surfaces of the devices look brown instead of gold, probably due to the contamination problem in the manufacturing process. It is believed that this brown color is not caused by the surface roughness of the gold because once the top surface is scratched with a probe tip, clean metallic gold can be observed. Furthermore, the brown color coating can be removed using Piranha; however, this process destroyed the nickel structural layer.

C. Hot and Cold Switching

Several short-term hot switching tests have been performed on relays with gold-to-gold contacts. The relays were used to hot switch an applied voltage from a dc power supply across a resistive load. The applied voltage was increased in discrete steps, and at each increment, the contact is opened and closed ten times. If the contact survives, the voltage is increased to the next level. The relays can hot switched up to 120 V and 0.46 A across a 250-Ω resistor, as shown in Fig. 11. Another experiment showed up to 50 V, and 1 A could be hot switched across a 50-Ω resistor. However, during the high-power hot switching process, contacts of these relays quickly deteriorate. Once the contacts fail, they often fail catastrophically, and the contact resistance jumps to several megaohms. The examination on a failed contact shows that the gold overcoat layer is gone, and the actual contact surface could be oxidized nickel.

Long-term hot-switching experiments are challenging since the contacts stop conducting after several hundreds to several thousands of cycles. The exact failure mechanism is unknown, but we suspect airborne contamination is one factor since the

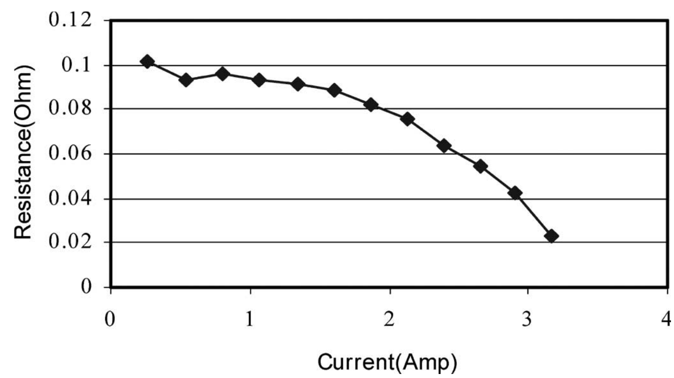


Fig. 12. Contact resistance versus carrying-current of a relay with liquid metal wetted contact.

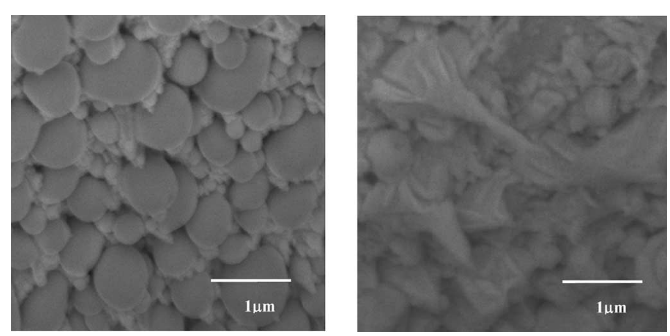


Fig. 13. Left: Close up of liquid metal wetted contact as fabricated. Right: After usage, it can be seen that the liquid metal has contacted opposing electrode and have been deformed.

TABLE II
COMPARISON OF TESTED GOLD-TO-GOLD AND LIQUID METAL COATED CONTACTS

Contact Type	Gold-to-Gold	Liquid-metal
On-state resistance (Ω)	0.3~0.4	0.015~0.1
Off-state resistance (Ω)	>100M	>100M
Max current carried (A)	4~5A	4~5A

relays are tested under normal atmospheric conditions without packaging. Experimentally, one relay has hot switched up to 10 V and 200 mA (2 W) for over 1000 cycles before failure. On the other hand, these microrelays can do cold switching for a much larger amount of power. Experimentally, 4 A and 200 V (800 W) can be passed without contact welding. Furthermore, a total of two relays were tested for over one million cycles continuously at 1 Hz for about 11.5 days. The operating voltage was kept the same throughout the test, and there is no observable decrease in displacement through the test.

D. Liquid Metal Contacts

In order to further reduce the contact resistance, the concept of liquid metal was applied. All of the functional liquid metal contacts are coated using the 0.1-ml Galistan fluid deposition process. Fig. 12 shows the current versus contact resistance of a liquid metal contact. Since the contact resistance is very low, accurate measurement is difficult. Any resistance in the measurement system such as connection wires, heating of the resistors, and probes will introduce errors. The figure shows best effort to eliminate the error by subtracting the parasitic resistance measured from the same contact pad, as described in the previous section. It was observed that when the current increases, the contact resistance decreases. This is due to local heating that causes the liquid metal to flow, which increases contact areas and reduces resistance. In a different liquid metal contact relay, a contact resistance as low as 0.015 Ω has been measured. Experimentally, both gold-to-gold and liquid metal coated contacts can pass about 4 to 5 A of current without contact welding. However, when a current of 4 A passes through a 0.02-Ω liquid metal coated contact, it only generates 0.32 W of heat, while 4.8 W of heat can be generated for a contact with resistance of 0.3 Ω. Although liquid metal coated contacts have low resistance, the probe tips used to test the relays get hot when the carrying current reaches 4–5-A level; hence, the liquid metal coated relays are not tested at higher current levels. Fig. 13 shows a liquid metal coated contact before and after operation, which verifies that the liquid metal droplets from opposing contacts can make connection and smear the liquid metal droplets. In general, the force required to obtain low liquid metal contact resistance is smaller than the gold-to-gold contact, but it is difficult to quantify the difference.

All of the liquid metal coated contacts that showed low contact resistance eventually failed by "bridging," when liquid metal connects the contacts in the OFF-state. This happens in less than ten switching cycles under high-carrying-current tests. It is believed that liquid metal flowed and permanently bridged the contact gap. Another possible failure mechanism is electromigration under high-carrying-current levels; this requires further investigations. If the carrying current is low, the relay can survive more switching cycles. Previous research on electrostatically actuated relays with mercury droplet contacts suffered from contact separation problems [54]. Since the separation force of the bidirectional actuator is comparable to the actuation force, both are in the neighborhood of several millinewtons. The current paper presents possible new class of microrelays using electrothermal electromagnetic actuators and liquid metal wetted contacts. Table II compares and summarizes the important characteristics of the liquid metal contacts versus gold-to-gold contacts presented in this paper.

V. CONCLUSION

We have demonstrated microrelays with gold-to-gold and liquid metal contacts that have many characteristics close to an ideal relay. These include low ON-state resistance, high-OFF-state resistance, high breakdown voltage, and good current carrying capacity. The voltage requirement to actuate these relays is very low, although the energy consumption to actuate these relays is high. The operational energy consumption can be significantly reduced using a bistable mechanical design, which will be further investigated. Future research would also include process improvement for liquid metal coating, reduction of the size of the magnet, and reliability testing of the liquid metal coated contacts.

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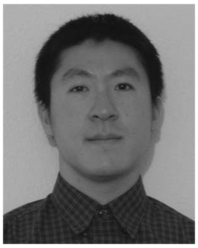

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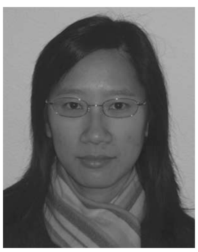

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